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# Evaluating crude oil chemical dispersion efficacy in a flow-through wave tank under regular non-breaking wave and breaking wave conditions

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ABSTRACT

Testing dispersant effectiveness under conditions similar to that of the open environment is required for improvements in operational procedures and the formulation of regulatory guidelines. To this end, a novel wave tank facility was fabricated to study the dispersion of crude oil under regular non-breaking and irregular breaking wave conditions. This wave tank facility was designed for operation in a flow-through mode to simulate both wave- and current-driven hydrodynamic conditions. We report here an evaluation of the effectiveness of chemical dispersants (Corexit® EC9500A and SPC 1000™) on two crude oils (Medium South American [MESA] and Alaska North Slope [ANS]) under two different wave conditions (regular non-breaking and plunging breaking waves) in this wave tank. The dispersant effectiveness was assessed by measuring the water column oil concentration and dispersed oil droplet size distribution. In the absence of dispersants, nearly 8–19% of the test crude oils were dispersed and diluted under regular wave and breaking wave conditions. In the presence of dispersants, about 21–36% of the crude oils were dispersed and diluted under regular waves, and 42–62% under breaking waves. Consistently, physical dispersion under regular waves produced large oil droplets (volumetric mean diameter or VMD $\geqslant$ 300 μm), whereas chemical dispersion under breaking waves created small droplets (VMD $\leqslant$ 50 μm). The data can provide useful information for developing better operational guidelines for dispersant use and improved predictive models on dispersant effectiveness in the field.



## 1. Introduction

The use of chemical dispersants can be an effective means to combat oil spills at sea (NRC, 1989, 2005). There has been renewed interest for the use of chemical dispersants due to escalated oil spill incidents, logistic constraints of traditional spill response options, and the development of new generation, low-toxicity, high efficiency dispersant formulations for potential use on oils covering a greater viscosity range (Chapman et al., 2007; Kirby and Law, 2008; Lessard and Demarco, 2000). Dispersant effectiveness depends on the chemical properties of both the dispersant and the oil and mixing energy from wave action (Fingas, 2000). Mixing results from shear forces in the water body due to both spatial and temporal variations in velocities. Velocity shear with its associated friction also causes the dissipation of kinetic energy of the fluid, which results in the breakup of an oil slick into tiny droplets and dispersion of the spilled oil into the water column, especially in the presence of a chemical dispersant. Sea currents add to the effect by diluting the dispersed oil droplets through advection and spreading. While advection moves them away from the source (i.e., the oil slick at the surface), spreading, which is caused by variation of velocity over space, causes the distance between droplets to increase. Therefore, currents have the tendency to increase the apparent dispersion effectiveness through dissipating the formed oil-in-water emulsion droplets away from the treated zone or curbing recoalescence of dispersed oil droplets by reducing collision frequency of dispersed oil droplets.

Bench-scale dispersant effectiveness tests (ASTM, 2002; EPA, 1996; Fingas et al., 1987) in the laboratory have been used for comparison of dispersant product effectiveness (Sorial et al., 2004a,b; Venosa et al., 2002) and for testing the effects of temperature, salinity, and other environmental factors (Chandrasekar et al., 2005, 2006; Srinivasan et al., 2007). However, laboratory tests for product selection suffer from the inherent limitation that, regardless of how closely flow fields are able to mimic mixing conditions at sea, current effects cannot be accommodated due to space constraints that influence transport and dilution effects. At the other extreme, field tests at sea are expensive and difficult to manage, and results are often inconclusive and non-repeatable due to lack of control of

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experimental and climatic conditions. Thus, wave tank studies have been suggested to generate needed operational data on both mixing energy and current effects so that chemical dispersion can be studied and evaluated reproducibly and repeatably in a setting that best simulates conditions at sea (NRC, 2005).

In anticipation of and in response to the requirements for testing the performance of chemical dispersants in more realistic oceanographic and environmental settings, the Department of Fisheries and Oceans Canada (DFO) and the US Environmental Protection Agency (EPA) built a wave tank facility. This wave tank was originally developed to evaluate dispersant effectiveness under different reproducible wave energy conditions with energy dissipation rates similar to those that are encountered in the field. The main goal was to relate quantitatively dispersant effectiveness with energy dissipation rate for varying dispersant formulae, oil types, and the weathering status of oil. Our wave tank experiments initially conducted in a batch mode configuration demonstrated the significance of wave conditions to chemical dispersant effectiveness (Li et al., 2008a,b; Venosa et al., 2008). However, hydrodynamic characterization of the wave tank operated in the batch mode also revealed the presence of back-flowing underwater currents counter to the direction of the progressive waves generated by the wave maker. This recirculation mechanism is caused by the surface Stoke's drift of the progressive waves (Wickley-Olsen et al., 2008) and is a necessary condition applicable to the conservation of water mass. To counteract the backward underwater current flow and to allow for simulation of natural exposure levels that result from dilution of dispersed oil in an open environment influenced by waves, tides, and currents, the wave tank was modified for operation in flow-through mode to simulate the influence of ocean currents. In this work, we studied dispersant effectiveness subjected to the combined actions of waves and currents. Specifically, we investigated the chemical dispersant effectiveness of two dispersants on two crude oils under regular non-breaking waves and plunging breaking waves while a current velocity equal to the Stokes drift of the progressing wave was applied to the system. Such an experimental system allows for dilution caused by the undersea current carrying away the dispersed oil plume.

## 2. Materials and methods

### 2.1. Wave tank description

Fig. 1 shows the schematic representation of the wave tank facility that was used in this research. The geometric dimensions are 32 m long, 0.6 m wide, and 2 m high. The average water depth was 1.50 m. Different waves were generated by a computer-controlled flap-type wave maker situated at one end of the tank. The wave maker is linked to an adjustable cam that controls its stroke to alter wave-heights. The wave frequency is controlled by the rotation speed of the cam. The computer-controlled wave generator can produce both regular non-breaking waves and breaking waves. The breaking waves are generated using the frequency sweep technique (Funke and Mansard, 1979), wherein a wave of one frequency is superimposed on another wave of a different frequency, causing the wave to increase in height until it breaks. The energy dissipation rate per unit mass ($\varepsilon$) was evaluated by the autocorrelation function method (Kresta and Wood, 1993) using a time series of velocity measurements obtained by an Acoustic Doppler Velocimeter (SonTec/YSI Inc., San Diego, CA) at select locations in the tank.

### 2.2. Wave conditions

Two wave conditions, namely regular non-breaking waves and plunging breaking waves, were generated and their hydrodynamics characterized. The regular non-breaking waves were generated with 12 cm stroke, 0.80 Hz frequency, 2.44 m wave length, and 23 cm wave height. The plunging breaking waves were produced with a 12 cm stroke and alternating trains of high-frequency waves (0.85 Hz, wave length 2.16 m, wave height 26 cm, and duration 20 s) and low-frequency waves (0.5 Hz, wave length 6.24 m, wave height 9 cm, and duration 5 s).

### 2.3. Current flow

A uniform current was introduced to the wave tank at a flow rate of 60 ± 2 gallon per min. This rate was selected to counteract the surface Stoke's drift velocity of the high-frequency (0.85 Hz) regular wave conditions. The component influent system includes uptake of seawater from the Bedford Basin (Dartmouth, NS, Canada), holding tank, electric pump, sediment trap and water filtration, flow meter, distribution pipes, control valves, and a water bypass for flow adjustment. The effluent system consists of outlets and valves, flow meter, electric pump, and wastewater treatment facility.

### 2.4. Dispersants

Two commercial chemical dispersants were tested, Corexit 9500 and SPC 1000. Both dispersants are listed in EPA oil spill contingency plan. The precise formulae of the dispersants are proprie-

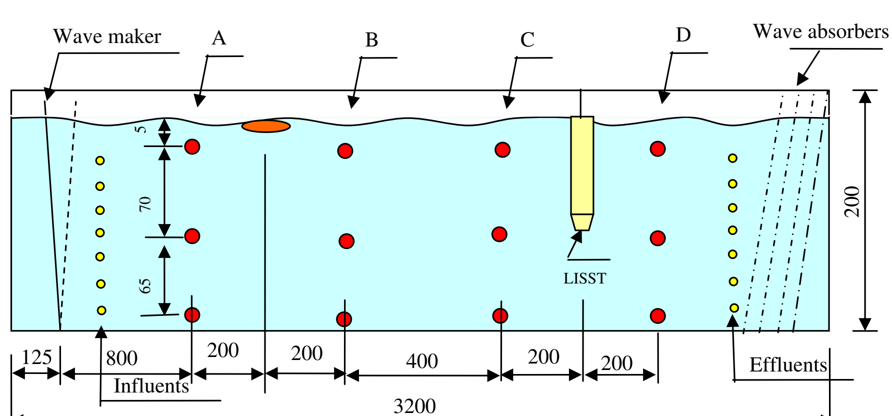


**Fig. 1.** Schematic representation (all dimensions in cm) of the wave tank facility. Larger circles represent four horizontal sampling locations: (A) 2 m upstream, (B) 2 m downstream, (C) 6 m downstream, and (D) 10 m downstream from the center of the spiked oil slick.